

SHORT REPORT

Simple and complex vestibular responses induced by electrical cortical stimulation of the parietal cortex in humans

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Abstract

The present study reports on a patient undergoing invasive monitoring for intractable epilepsy who experienced different vestibular sensations after electrical cortical stimulation of the inferior parietal lobule at the anterior part of the intraparietal sulcus. Types of vestibular response ranged from simple to complex sensations and depended on stimulation site and applied current. The findings suggest vestibular topography and hierarchical processing within the parietal vestibular cortex of humans.

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As we move through space many different sensory inputs are combined to constantly update the spatial relation between our body (personal space) and our surroundings (extrapersonal space). Whereas the extrapersonal space is largely perceived by the visual and auditory senses, the vestibular system has a fundamental role in the perception of the personal space, defining the motion, position, and movement of our body. However, in comparison to the wealth of data on the visual and auditory cortical system in primates, little is known about cortical processing of vestibular information.^{1–3} Moreover, these vestibular representations have been found in widespread cortical areas including the temporal, the parietal, and the frontal lobes, leading to the suggestion that a primary vestibular cortex might not exist. In humans, evidence for a vestibular cortical system is even more sparse, but electrical cortical stimulation (ECS)^{4–5} and focus localisation in epileptic patients with vestibular auras⁶ suggest cortical vestibular processing in the perisylvian area. More recent studies using brain imaging techniques during caloric vestibular stimulation^{7,8} and during galvanic vestibular stimulation^{9,10} in normal subjects, as well as testing of the subjective verticality in patients with circumscribed brain lesions,¹¹ have confirmed vestibular processing in the perisylvian location.

A human parietal vestibular cortex has been described in an old case report using ECS,¹² in

a study using caloric vestibular stimulation and PET⁸ and in a recent study which combined galvanic vestibular stimulation and functional MRI (fMRI).⁹ These studies localised this vestibular site to the inferior parietal lobule. However, galvanic vestibular stimulation leads to somatosensory or painful sensations during the stimulation procedure, which made it difficult to dissociate vestibular from somatosensory or nociceptive cortical activation patterns. Moreover, previous studies did not investigate whether different sites within the parietal vestibular cortex process different types of vestibular information (rotation, linear acceleration, or more complex forms of vestibular processing).

The present study reports on a patient undergoing invasive monitoring for intractable epilepsy who experienced different types of vestibular sensations after ECS of distinct sites of the left inferior parietal lobule.

Patients and methods**PATIENT REPORT**

A 23 year old male right handed student had complex partial seizures since the age of 12. After non-invasive presurgical evaluation for pharmacoresistant epilepsy, the epileptic focus was suspected in the left hemisphere. Brain MRI showed polymicrogyria in the left inferior frontal gyrus. To localise the epileptic focus, primary motor and somatosensory cortex, and cortical language centres, the patient was referred for intracranial seizure monitoring by subdural grid electrodes.¹³ This showed two epileptic foci: seizures originated predominantly from the left temporal lobe and in about 20% from the dysplastic region in the inferior frontal gyrus.

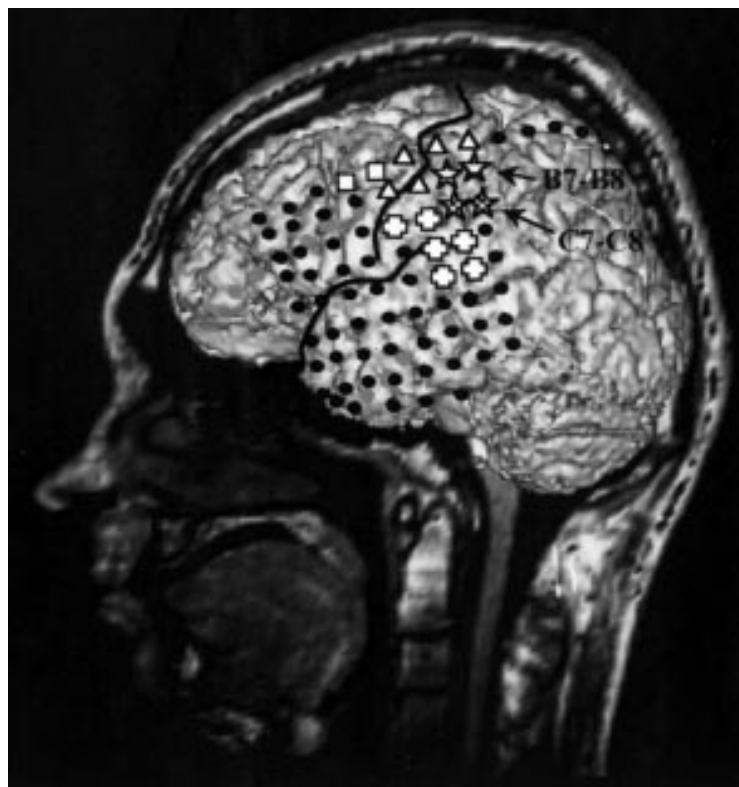
ELECTRICAL CORTICAL STIMULATION

Electrical cortical stimulation was performed via 88 subdural grid electrodes (Ad-Tech, Racine, WI, USA) placed over the lateral surface of the left hemisphere, covering parts of the frontal, parietal, and temporal lobe. The location of the MRI compatible electrodes (3 mm diameter stainless steel, centre to centre distance: 0.8 cm) was determined by acquisition of three dimensional MRI images with the implanted electrodes (figure) and subsequent transformation

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Localisation of cortical responses as found by stimulation mapping in the patient. Responses included vestibular responses (star), face or tongue movements (square), facial or lingual somatosensory responses (triangle), and language responses (cross). Black circles represent those sites at which no overt responses were evoked. The central sulcus and the Sylvian sulcus are indicated (black lines). Electrical cortical stimulation at electrodes B7-B8 (star with horizontal lines) evoked sensations of vertical linear and rotational contralateral body movement. At electrodes C7-C8 (star with small squares) the sensation of an alternating right-left whole body movement was induced. Note the proximity of vestibular and somatosensory responses at the junction of the anterior part of the inferior parietal lobule and the postcentral gyrus. Language responses were found at the parietotemporal junction. The three dimensional MRI is turned and rotated to better visualise electrode positions covering the parietal lobe.

of the T1 weighted MRI image into Talairach space¹⁴ using a 12 parameter linear transformation. The patient was comfortably sitting in bed, unrestrained, with the legs in supine position and the upper body raised at about 45 degrees. The ECS procedure was carried out as described elsewhere.¹⁵ No afterdischarges occurred during ECS in the parietal lobe.

Results

Vestibular responses (VRs) were evoked at two sites (four electrodes in a bipolar montage) in a total of 35 trials. The VRs were evoked immediately posterior to the somatosensory rep-

resentation of the lower face and tongue and superior to the posterior language cortex (figure). These sites were positioned at the junction of the intraparietal sulcus with the postcentral gyrus. The Talairach coordinates of the electrodes which evoked VRs are given in table 1 and located in the anterior part of Brodmann's area 40 (anterior part of the inferior parietal lobule).

The initial responses at electrodes B7-B8 (4.5–5.5 mA, 2 s) resulted in a sensation that the patient described as if he were “sliding towards the lower end of the bed”. At higher currents the patient described the sensation of right-sided body rotation which was reported as “I’m rolling to the right and falling out of the bed”. On questioning, no motion of his visual surrounding was noted. Stepwise increase of current amplitude (by 0.5 mA) intensified the second vestibular sensation (“I feel the urge to hold on to something in order to prevent myself from falling out of the bed”, 5.5–8.0 mA, 2 s). Eventually, this rightward sensation of falling led to a very strong and unpleasant sensation and the patient clammering on to the bed which he now perceived as rotating with him to the right (5.5–8.0 mA, 2 s). Eye closure did not alter the VR. No sensation related to linear acceleration was reported by the patient at stimulation currents above 5.5 mA. ECS at the same site while the patient read from a journal held in his hands changed the vestibular sensation. He now also perceived the journal to be turning with him to the right (10.5 mA, 5 s). No surround motion in his visual field (ceiling, walls, floor, etc) was noted during ECS (4.5–10.5 mA). Neither eye deviations or eye cyclotorsions nor a change in head position were seen. No nausea or vomiting was noted. Reading and speech abilities were not impaired during ECS during all trials.

During ECS at electrodes C7-C8 (8.0 mA) the patient perceived constantly alternating side to side rotation of his entire body without visual surround motion. The initial report by the patient after the first ECS at 8.0 mA “my whole body moves” was described more precisely during restimulations with identical currents when the patient reported that he felt as if he were lying in a swinging hammock. When asked to describe what he felt he indicated this sensation by swinging both arms with alternating movements from right to left. During the stimulation the patient showed slowing during counting and naming tasks, although no specific speech problems were found.

Discussion

In this patient unidirectional and bidirectional vestibular sensations could be induced by electrical interference at two different cortical sites at the anterior part of the intraparietal sulcus. These responses suggest that the vestibular cortex—as the other sensory systems—is characterised by a hierarchical organisation. The functional and anatomical location provides further evidence that this vestibular site is distinct from the somatosensory cortex and might represent the human homologue of area 2v.¹

Table 1 Anatomical location of the left parietal vestibular cortex (Talairach coordinates)

Authors	Method	x	y	z
Bottini <i>et al</i> ⁸	Caloric vestibular stimulation, PET	-48	-34	24
Lobel <i>et al</i> ⁹	Galvanic vestibular stimulation, fMRI	-48	-12	48
		-52	-28	52
Dieterich <i>et al</i> ¹⁶	Optokinetic stimulation, fMRI	-42	-38	32
Sunaert <i>et al</i> ¹⁷	Optokinetic stimulation, fMRI	-30	-44	52
Present study	Electrical cortical stimulation			
	mean	-60	-53	22
	B7	-62	-46	21
	B8	-62	-59	23
	C7	-57	-45	21
	C8	-57	-60	23

Mean location is indicated in Bottini *et al*; location of the two voxels with the highest significance is given in Lobel *et al*; location of the voxels with highest significance is given in Dieterich *et al* and Sunaert *et al*; the location of each electrode as well as mean are given for this study. Note that bipolar stimulation was carried out between adjacent electrodes (B6-B7, C7-C8).

The anatomical location and the unilateral vestibular responses of our patient correspond well with an early report of two epileptic patients,¹² who described their vestibular sensation induced by ECS as “hold me, I’m rolling off the table”. Our patient also perceived a contralateral rotation of the body as well as contralateral falling with respect to a stable visual background (walls, floor, ceiling, doors, etc). Furthermore, this electrically induced sensation may not only affect the body proper, but also those parts of the extrapersonal space that are in contact with the body (journal, bed). The location of electrodes leading to VRs is somewhat more posterior and lower than found by neuroimaging studies using caloric vestibular,^{7, 8} galvanic vestibular,⁹ or optokinetic stimulation.^{16, 17} However, the proposed site of the parietal vestibular cortex is variable across studies (table). These differences, however, should not be overestimated given the important methodological differences between study protocols (galvanic vestibular stimulation, caloric vestibular stimulation, or optokinetic stimulation, fMRI, PET, ECS) and the fact that either the mean locations⁸ or the location of voxels with the highest significance were reported.^{9, 16, 17} Lobel *et al*⁹ found a large activation extending from the postcentral gyrus to the intraparietal sulcus. However, as all subjects of the last study reported the feeling of either a metallic taste or pain during galvanic vestibular stimulation, it cannot be excluded that the activation pattern on the postcentral gyrus might result from coactivation of the somatosensory cortex. The data in our patient show that pure vestibular responses can be induced from the postcentral gyrus and the adjacent cortex around the intraparietal sulcus. Furthermore, the parietal vestibular cortex in our patient was anatomically distinct from the somatosensory cortex. The minor differences in anatomical location of the parietal vestibular cortex as determined by various study protocols and the similar anatomical and functional location immediately posterior of the somatosensory representation of the face—as in monkeys¹—suggests that this parietal site represents the human homologue of area 2v.

Our results have to be applied with caution to normal brain function as stimulations have been carried out in an epileptic patient. However, the localisation of sensorimotor and language functions in this patient do not suggest grossly deviant brain pathology for anatomical representations of cortical functions. Furthermore, the seizure foci were found distant from the area under investigation, and the patient had never experienced vestibular sensations during his habitual seizures. It should also be mentioned that the clinical situation did not allow for more detailed testing of vestibular function.

It has been repeatedly shown that the human cortex is involved in processing of information that arrives from the semicircular canals.^{4–10, 12, 16, 17} Our findings extend previous results and suggest that the subjective strength of the stimulation induced sensation of body

rotation correlates positively with the amplitude and duration of the applied current. If we assume that electrically induced responses result from activation of underlying neurons our findings suggest that more intense VRs are caused by either a higher and longer activation of the identical neuronal population or the activation of a larger population of cortical vestibular neurons.

We also induced—at the adjacent parietal site—the sensation of alternating side to side body rotation. This response, which represents an increase in complexity if compared with unidirectional vestibular responses, is suggestive of higher level vestibular processing which has not yet been shown for the vestibular cortex.^{1–3, 18} In the primate visual and auditory system, cortical hierarchy based on intra-areal laminar connectivity patterns has been established to account for the progressive increase of complexity of the receptive field properties of single neurons.¹⁸ In humans, visual responses during ECS have also provided evidence for hierarchical cortical processing and Penfield *et al*⁶ showed that the perception of small stable phosphenes and the perception of coloured objects and forms can be induced by ECS of the striate and the extrastriate cortex respectively. Analogous to these findings, we suggest that the sensation of unilateral body rotation represents simple vestibular cortical processing, whereas bilateral alternating body rotation represents a higher level of cortical vestibular processing, suggestive of hierarchical organisation in the parietal vestibular cortex.

Finally, whereas vestibular cortical processing related to linear acceleration has been suggested in epileptic patients⁶ it has not been shown in other studies either in monkeys or humans. Even if responses related to body rotation predominated in our patient, the sensation of directional vertical sliding of the whole body suggests the involvement of the inferior parietal lobule in processing of linear motion of the self.

In memoriam—Professor Otto-Joachim Grüsser.

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